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Target Strength Measurements on Metal Spheres

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Target Strength Measurements on Metal Spheres

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Introduction

The estimation of fish abundance by the echo-integrator method requires a sonar that has been accurately calibrated. This may be done by measuring the signal received from a target whose acoustic properties are known. Several kinds of metal spheres have been used as calibration targets, in particular brass (Forbes, Simmonds and Edwards, 1980), copper (Foote, *et al.*, 1981) and tungsten carbide spheres (Dragonette, Numrich and Frank, 1981).

The back scattering properties of the target are described by the target strength (TS) and the error in a calibration depends upon the accuracy of the TS value assumed for the sphere. If the sound velocities within the sphere are known, the target strength may be derived from scattering theory (Hickling, 1962), or it may be measured experimentally. In favourable circumstances, when the sonar frequency is not too close to a mechanical resonance frequency of the sphere it is considered that the theoretical target strength estimate is the more precise (MacLennan, 1981). The accuracy of present techniques for making absolute acoustic measurements is generally poor, but it is nevertheless important that theoretical predictions should be tested by experiment. This may be done by comparing one target with another, since relative acoustic measurements are capable of sufficient accuracy to test the theory.

In the experiments described here, the target strength differences between pairs of spheres were measured. A total of eight spheres were included in the tests, comparing one brass, two copper and five tungsten carbide spheres. The main aim was to measure the target strength differences between these three types of sphere, but differences between spheres of the same nominal specification were also investigated. The experiments were all conducted with a 38 kHz sonar. This is the frequency that is normally used on acoustic surveys of fish stocks.

Definition of the Target Strength

In this paper, the target strength in dB is defined by the equation:

$$TS = 10 \log_{10} (R^2 E_1 / E_0) \quad \ldots\ldots (1)$$

where E_1 is the energy in the receiver output signal from the target at range R. E_0 is the energy in the signal that would be obtained if the receiving transducer had replaced the target, in other words if the incident pressure wave were applied to the receiving transducer. It is assumed that the target is on the acoustic axis and in the far field of the transmitting transducer.

This TS accords with the definition proposed by Foote (1982) to take account of the system frequency response, but it is not the same as the perceived target strength (TSp) which was defined in MacLennan (1981). Equation (1) is a more convenient description of targets which may be used

to calibrate different sonars since TS is less dependent on the pulse length and the sonar frequency response. The difference between TS and TSp is independent of the target; thus for a particular sonar, (TS – TSp) is a function of the pulse length alone. The relationship is:–

$$TS = TSp + 10\,Log_{10}\left\{\int_{-\infty}^{+\infty} |g(f)|^2\,df \Big/ \int_{-\infty}^{+\infty} |F(f)G(f)g(f)|^2\,df\right\} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Here f is the frequency, g(f) is the spectrum of the transmitter input pulse, F(f) and G(f) are the transfer functions of the sonar in transmit and receive modes respectively.

Transfer functions for the 38 kHz sonar used in the experiments reported here were described in MacLennan (1981). The results in that paper may be converted to equivalent TS values by adding the factors shown in Table I.

Table I

Differences between TS and TSp for the 38 kHz sonar used by Forbes *et al.* (1980) and in the experiments reported here.

Pulse length (ms)	TS – TSp (dB)
0.5	+0.41
1.0	+0.20
2.0	+0.10
3.0	+0.06

Equipment and Methods

The targets to be compared were suspended by monofilament nylon twines from the triangular frame of a pan-tilt unit designed by Dennard Ltd (Fig. 1). The transducer (Simrad 38 kHz ceramic) could be rotated relative to the frame around two axes. The transducer could be moved under remote control by means of electric motors and the rotations about the axes were measured by angle encoders to a resolution of 0.05°.

The complete assembly was suspended at 20 m depth below a moored raft in a sea loch. The drive motors, angle encoders and the transducer were connected by cables to a shore station where an online LSI4 computer was used to control the system and to collect data. A block diagram of the system is shown in Figure 2.

The targets were positioned about 4 m and 5.5 m from the transducer face respectively. This separation was just sufficient to allow the reflections of a 1 ms long pulse to be resolved. The twine lengths were adjusted so that the angle between the targets as seen from the transducer was less than 1.5°.

The echo signals were processed by a fixed gain amplifier (time varied gain was not applied) and the detector output was sampled at 0.1 ms intervals. The energy in the reflected pulse from each target was estimated by squaring and adding the samples for which the pulse amplitude was significantly above noise level. For each position of the transducer, the pulse energies were computed for 40 transmissions at a rate of three transmissions per second. The mean and standard deviation of the results were computed for each target. The data were accepted only if the standard deviations were less than 5% of the corresponding means, otherwise the 40 transmissions were repeated.

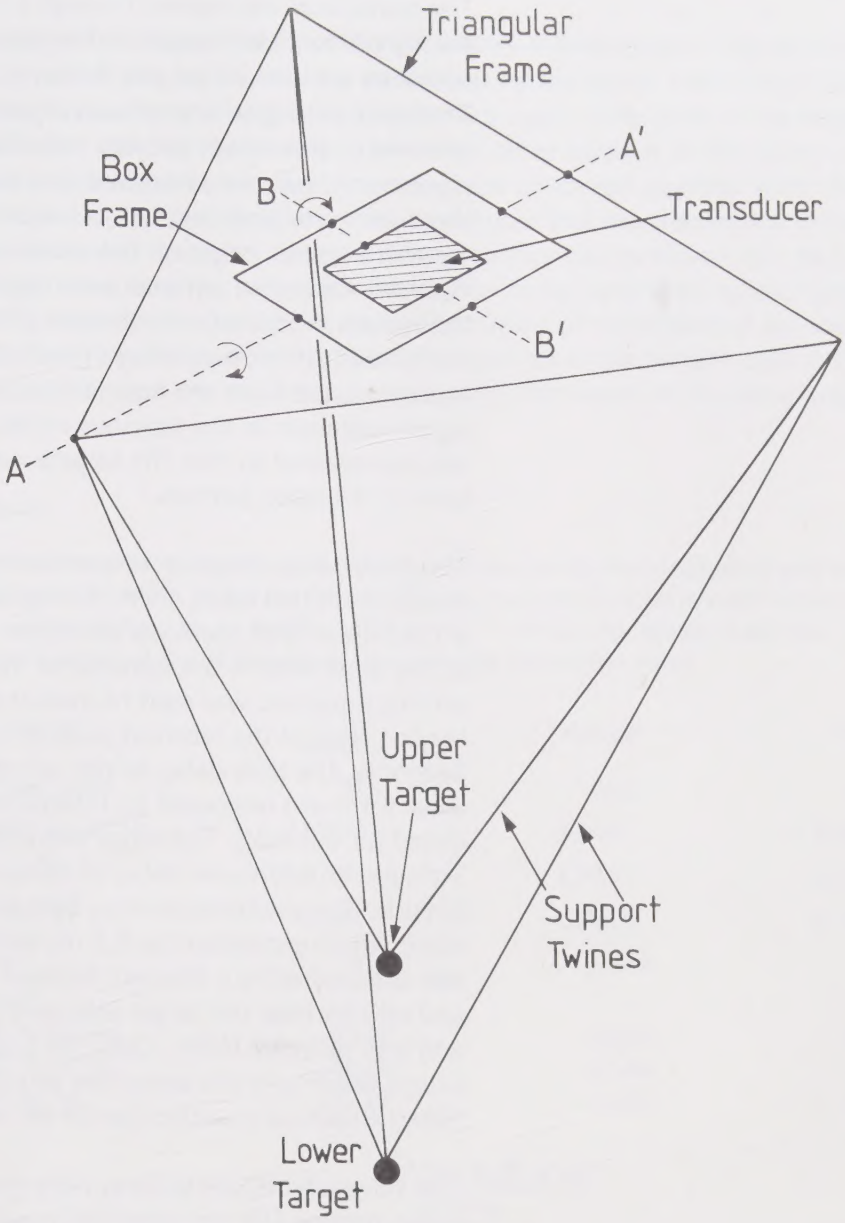

Figure 1. Experimental rig for the comparison of two targets. The transducer is rotated about the axes AA′ and BB′ to locate each target on the acoustic axis.

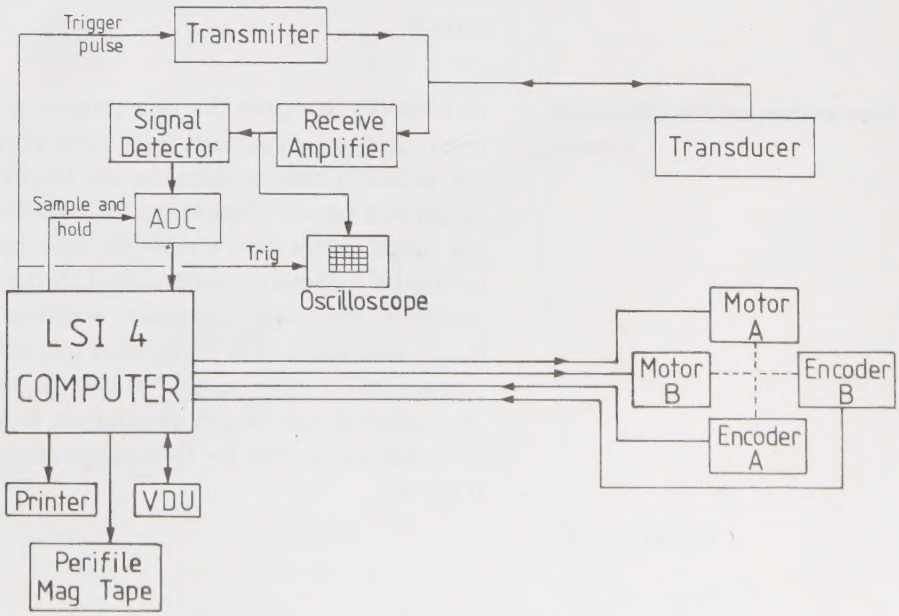

Figure 2. Block diagram of the measurement system.

The transducer was moved through a cycle of positions in order to estimate the signal from each target on the acoustic axis. This cycle consisted of nine positions about the first axis followed by nine positions about the second. The range of angles covered was chosen so that the pulse energy at the extreme positions was not less than 85% of the maximum value. A quadratic regression curve was computed for each set of nine measurements to estimate the maximum signal and the corresponding angle for each target. Finally, the signal from each target on the acoustic axis was estimated by interpolation. Approximately ten minutes were required to complete one such cycle, so the system produced six estimates of the maximum signal from each target in an hour. At the beginning of each cycle, the central transducer position was computed from the mean of the positions corresponding to maximum signals obtained in the previous cycle. Thus the movement of the transducer was constrained so that the targets were always located well within the main lobe of the beam pattern.

The time delays between the transmitted and the reflected pulses were measured in two ways. First, the signal at the detector input was viewed on a Tektronix 7603 oscilloscope whose time base (type 7B53A) was triggered at the same time as the transmitter input pulse. The delay multiplier facility on this time base was used to measure the pulse delay to a point 50% up the leading edge of the received pulse with respect to the asymptotic amplitude. Secondly, the time delay to the corresponding point on the detector output wave form was measured by interpolating between the 0.1 ms samples produced by the ADC. The latter was the more accurate timing method but it included an additional delay of about 0.07 ms introduced by the detector circuits. The oscilloscope time base was calibrated against the 10 kHz crystal clock which generated the 0.1 ms sampling interval, and the clock frequency was checked using a Hewlett Packard 5315B counter. The water temperature and salinity near the target assembly were measured by a DNW5 wave height and tide recorder (NBA Controls Ltd) which was moored near the raft. The sound velocity in the water was calculated from these data using a well established empirical equation (pp 94-95 in Urick, 1967).

The tungsten carbide spheres were supported by a net bag constructed from nylon netting (18 mm stretched mesh size, 0.3 mm twine diameter) laced with 0.7 mm diameter monofilament nylon. The copper spheres were supported by a webbing made from 0.5 mm diameter monofilament nylon twine. The total length of twine in the webbing was about 1.2 m. The brass sphere had a 3 mm diameter hole drilled through it. In this case the suspension twines were passed through the hole, then knotted to support the sphere.

Correction of the Observed Signals

In order to compare the two targets in terms of the signals that would have been received under identical conditions, the observed signal ratio must be corrected to take account of the target range, forward scatter by the upper target and sound absorption in the water. The most important of these is the range correction. Under far field conditions the received pulse energy would be inversely proportional to the fourth power of the range to the centre of the target. However, a theoretical calculation of the on-axis transducer sensitivity was performed in order to obtain a more precise range correction. It was found that the deviation from far field conditions was very small at the ranges of interest. For example, in the case of targets at 4 m and 5.5 m, the far field range correction was found to be in error by 0.03 dB.

The range R is estimated from the time delay measurement. The range is equal to half the sound velocity multiplied by the sound travel time from the transducer to the target centre and back again. The latter is the measured time delay reduced by an amount τ which takes account of the point on the pulse waveform at which the time delay was measured together with the additional delay contributed by the transducer and the electronics. τ has been estimated from the theoretical received waveform which may be computed from scattering theory and the sonar model described in MacLennan (1981). Values of τ (excluding the contribution of the detector) are shown in Table II together with the physical properties of the targets used in the computation and the theoretical target strengths based on the same property values.

Table II

Physical properties of the targets. c_1 and c_2 are respectively the longitudinal and transverse sound velocities within the sphere. TS is the theoretical target strength which has been calculated for a water density 1,030 kg m^{-3} and sound velocity 1,490 m s^{-1}. T is the pulse length of the 38 kHz signal applied to the transmitter input.

Target	Tungsten carbide	Copper	Brass
Diameter (mm)	38.1	60.0	69.9
Density (kg m^{-3})	14,860	8,945	8,360
c_1 (m s^{-1})	6,655	4,760	4,372
c_2 (m s^{-1})	3,984	2,288.5	2,100
τ(ms)	0.08	0.11	0.24
TS (dB)			
for T = 0.5 ms	−42.27	−33.58	− 32.74
T = 1.0 ms	− 42.32	− 33.54	− 33.23
T = ∞	−42.37	− 33.51	− 33.76

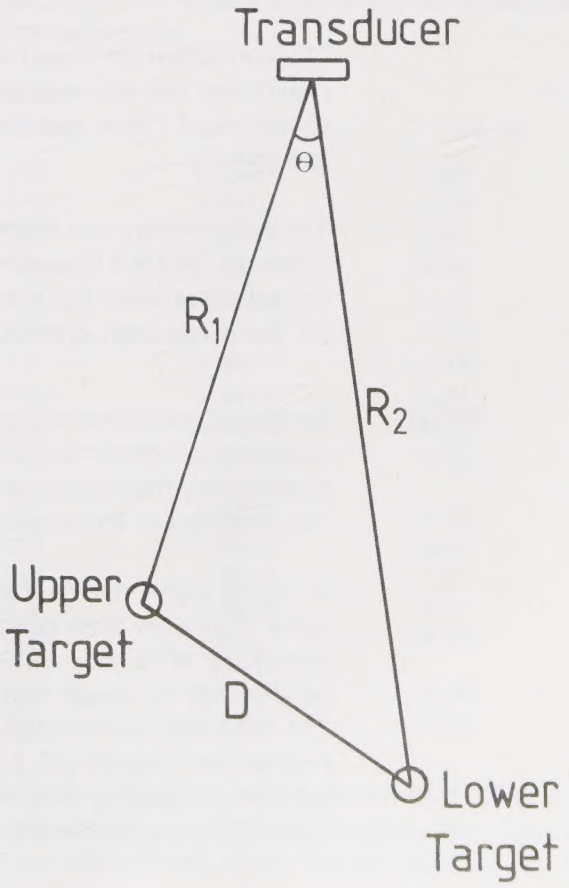

Figure 3. Geometry of the targets relative to the transducer.

The forward scatter correction is also significant. It arises because the upper target adds a forward scatter component firstly to the transmitted pulse, and secondly to the reflected pulse from the lower target. A first order correction may be computed from continuous wave theory. Consider the geometry illustrated in Figure 3. Since the separation between the targets is large compared to both the wave length and the target diameter, far field conditions apply. The forward scatter waves spread spherically from the centre of the upper target. If I is the intensity of the lower target reflection at the transducer and I_0 is the intensity that would have been received in the absence of the upper target, it can be shown that:-

$$\frac{I}{I_0} = \left| 1 + \frac{af}{2D} (R_2/R_1) \exp (-ik \left\{ R_1 + D - R_2 \right\}) \right|^4 \quad \ldots\ldots\ldots\ldots (3)$$

Here f is the far field form function for forward scattering, a is the upper target radius, k is the wave number, and the distances are as shown in Figure 3. The exponential term takes account of the interference between the forward scatter and the direct signal components when the targets are not in line. It has been assumed, however, that the angle θ between the targets is much smaller than the transducer beamwidth.

A tungsten carbide sphere was always used in the upper position since this target introduced the least forward scatter contribution. The form function is obtained from scattering theory. At 38 kHz, the far field forward scatter form function of the tungsten carbide sphere specified in Table II is:—

$$f = 2.02 \exp (-0.95i) \quad \ldots\ldots\ldots\ldots (4)$$

f is of course a function of θ, but the variation is a second order effect which may be ignored in this application.

Considering again the example of targets at 4 and 5.5 m range, the forward scatter correction is – 0.18 dB when the targets are in line, and it increases to 0 dB when $\theta = 1.3°$.

The correction for sound absorption is small. The one-way absorption coefficient was assumed to be 0.008 dB m^{-1}, in accordance with the equations of Fisher and Simmons (1977) for the prevailing temperature and salinity.

The pulse energy was estimated by the sum of discrete samples at 0.1 ms intervals. This is a biassed estimate of the complete integral, but calculations indicate that when the pulse length is 1 ms, the bias is always less than 0.01 dB and it has been ignored.

Results

Seventeen experiments were carried out on ten target pairs, including seven repeat experiments as a check on the consistency of results. Prior to each experiment, the targets were soaked in soap solution for one hour or longer. The duration of an experiment was at least six and often more than 12 hours.

A typical signal record is shown in Figure 4 where each point is the maximum signal estimated from one cycle of transducer movements. Changes in the transducer efficiency and/or receiver sensitivity show up as a correlated variation of the target signals, and they have no effect on the signal ratio. The latter did nevertheless exhibit a very slow fluctuation, generally within a range not exceeding 0.2 dB. The occasional spike on the signal record was probably caused by wild fish whose signals were not large enough to be rejected by the 5% limit on standard deviations.

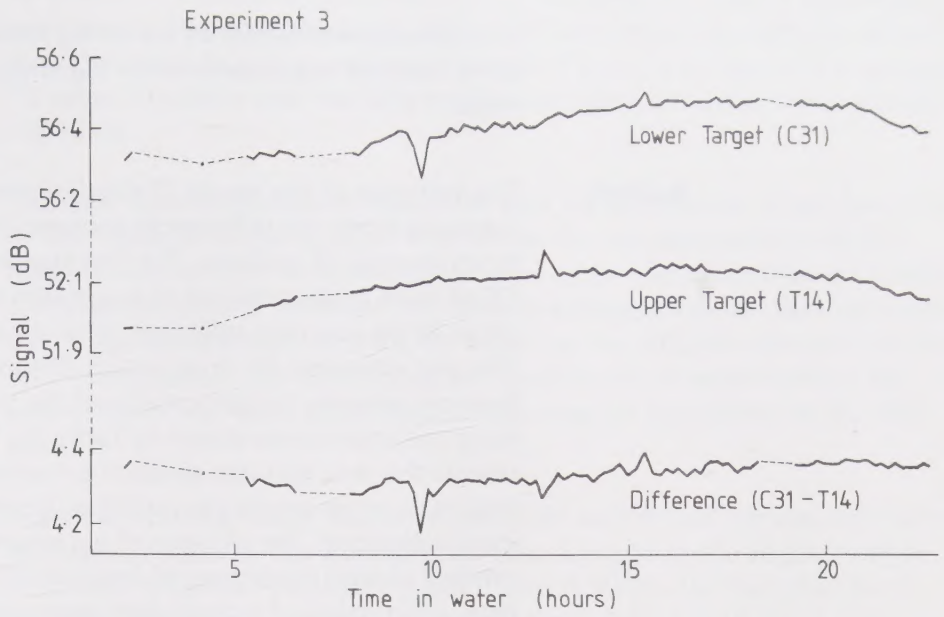

Figure 4. Typical record of the reflected pulse energy from a copper and a tungsten carbide sphere. The origin of the vertical scale is arbitrary, except for the signal difference.

Results from the 17 experiments are shown in Table III. Each target has been identified by a number and a letter, T for tungsten carbide, C for copper and B for brass. The target strength difference has been computed from the average on-axis signal ratio recorded during an experiment, but omitting the first hour after the targets were lowered into the water. Corrections were calculated as described in the previous section, then added to the observed signal ratio to give the estimates of the difference in target strength.

Table III

Experimental results. ΔTS is the target strength difference between the lower and the upper targets. T is the pulse length.

Upper target	Lower target	c ($m\ s^{-1}$)	Δ TS (dB) T = 1.0 ms	Δ TS (dB) T = 0.5 ms
T14	T15	1,490.1	+0.06	–
T14	T15	1,491.4	–0.08	–
T14	T20	1,491.3	–0.02	–
T14	T20	1,491.9	–0.06	–
T14	T21	1,491.0	–0.35	–
T14	T21	1,491.9	–0.12	–
T14	T21	1,491.4	–0.18	–
T14	T22	1,491.0	–0.27	–
T14	T22	1,490.5	–0.34	–
T15	T22	1,491.4	–0.16	–
T14	C31	1,491.3	+8.53	+8.52
T14	C31	1,490.6	+8.59	–
T14	C32	1,490.6	+8.57	+8.47
T15	C32	1,491.9	+8.54	–
T15	C31	1,492.5	+8.79	–
T14	B11	1,490.7	+9.09	+9.56
T14	B11	1,492.2	+9.24	–

Most of the results were obtained with a transmitter pulse length of 1 ms. A few measurements were made with 0.5 ms pulses. However, the asymptotic pulse amplitude was less evident at the shorter pulse length. The 0.5 ms data

were therefore obtained by switching between the two pulse lengths and using the time measurements on the longer pulses to estimate the target range.

Analysis

The variation of the results (Table III) may arise from experimental error or it may indicate real differences between the targets. This may be investigated by an analysis of variance. The first step is to obtain best estimates of the TS of seven targets relative to a common reference. For convenience, T14 is taken as the common reference since it was most often in the upper position. The best estimates are those which minimise the sum of squares of the differences between the estimated and the measured target strengths. Results from this analysis are shown in Table IV. The residual sum of squares represents the variation that cannot be explained by differences between the targets, in other words the variation caused by errors inherent in the measurement technique. The variance of a measurement is estimated from this residual divided by degrees of freedom. There are ten degrees of freedom here, the number of independent measurements (17) less the number of unknowns (7). The standard deviation of a measurement is found to be 0.09 dB. The experimental error may also be expressed in terms of confidence limits. From tables of Student's t-distribution, the 95% limits on one measurement are ± 0.21 dB. This means that there is a 95% chance of one relative TS measurement being within ± 0.21 dB of the "true" value, namely the average which would be obtained from a large number of repeat measurements.

Table IV

Best estimates of target strengths relative to T14. MT is the mean of the five tungsten carbide spheres and MC is the mean of the two copper spheres. The limits refer to 95% confidence levels.

Target	Δ TS (dB)
T15	− 0.07 ± 0.11
T20	− 0.04 ± 0.15
T21	− 0.22 ± 0.12
T22	− 0.28 ± 0.13
C31	+ 8.61 ± 0.13
C32	+ 8.52 ± 0.16
B11	+ 9.16 ± 0.15
MT	− 0.12 ± 0.05
MC	+ 8.57 ± 0.11

It has been assumed here that the same measurement error applied to all the experiments. While this assumption may be questioned, there is no evidence from the experimental results to support a different hypothesis. It might be supposed that the signals from the larger targets would be the more stable, for example if surface contamination were a significant cause of variation. However, such an effect would have little influence on the observed variance since the target pair always included at least one of the smaller tungsten carbide spheres.

It is useful to consider the implications of the error analysis for the accuracy of sonar calibrations. It seems likely that the measurement variance is mainly associated with random changes in the acoustic properties of the targets, including the contribution of the netting support and any entrained gas, and with errors in timing the reflected pulses. The corresponding

variations of the two target signals will be uncorrelated. Now a calibration is performed using only one target, so in that case the variance should be half that applicable to a two-target experiment. If there is no bias in the assumed TS value, it follows that the 95% confidence limits on a calibration should be ± 0.15 dB.

The least squares analysis expresses the best TS estimates as linear functions of the measured target strength differences. On the assumption that the measurement error is uncorrelated between experiments, confidence limits on these estimates or on linear combinations thereof may be obtained from the single measurement variance, by summing the variance contribution from each measurement that contributes to the estimate. In what follows, the limits shown with each result indicate the range of significance at the 95% level.

Significant differences of the order of 0.2 dB were found between the tungsten carbide spheres. For example, the best estimate of the target strength difference between T20 and T22 was 0.24 ± 0.19 dB. On the other hand, the difference between the two copper spheres, 0.09 ± 0.19 dB, is not significant.

The difference between the mean of the two copper spheres and the mean of the five tungsten carbide spheres was found to be 8.69 ± 0.11 dB. This is in good agreement with the value predicted by theory, 8.78 dB at 1 ms pulse length. While the experimental results do not directly confirm the absolute target strengths predicted by the theory, they do support the conclusion that the latter should be correct to within 0.1 dB when the mechanical resonances of the sphere are far removed from 38 kHz (MacLennan, 1981).

In the case of the brass sphere, there is a resonance close to 38 kHz and the theoretical predictions are relatively imprecise, – 33.2 ± 0.7 dB at 1 ms pulse length. A better value may be obtained from the measurements relative to the other spheres and making use of the more precise theoretical target strengths of the latter. This partly experimental target strength of the brass sphere is found to be – 33.0 ± 0.2 dB for 1 ms pulses. The two estimates are in agreement within the confidence limits specified.

According to the theory, the target strength of the brass sphere should be 0.5 dB higher for 0.5 ms pulses. The one measurement done at the shorter pulse length supports this result. Thus the brass sphere TS at 0.5 ms pulse length is estimated to be – 32.5 ± 0.2 dB.

The mean sound velocity during the brass sphere experiments was 1,491.4 m s^{-1} corresponding to a water temperature of 12.4° C and salinity 29.8 parts per thousand. Because of resonance effects, the variation of the target strength with the sound velocity in water is significant and the target strength should be adjusted accordingly. The coefficient of TS variation with the sound velocity has been calculated to be +0.02 dB s m^{-1}, and this corresponds to a temperature coefficient at constant salinity of +0.07 dB $°C^{-1}$.

Conclusions

The target strengths of the five tungsten carbide spheres were spread over a 0.28 dB range. This is more than the ± 0.1 dB range which theory suggests should be the maximum. It is not known whether the differences between the spheres arose from non-uniformity in the elastic properties of the metal, from a variable contribution of the netting bag or surface contamination. The net bags used in these experiments contained more knots and bunched

material than the twine webbing which supported the copper spheres. The use of the neater webbing support with the tungsten carbide spheres could improve matters, to the extent that the net bag was responsible for the observed variation. Further work is required to clarify this point. Nevertheless, the mean target strength difference between the copper and the tungsten carbide spheres agreed with the theoretical prediction within the limits of experimental error, ie within 0.1 dB. This result supports the theoretical basis on which the absolute target strengths have been calculated. Both the tungsten carbide and the copper spheres have been shown to have satisfactory properties for the calibration of sonar equipment at 38 kHz.

The brass sphere is not recommended as a precision target for calibration purposes because of the resonance problem. However, since this sphere has been used as a reference in fish target strength experiments, it has been necessary to obtain the best estimate of the target strength. This has been done by combining relative TS measurements on the brass sphere with the more reliable theoretical target strengths of the other spheres.

Acknowledgements The author wishes to thank Mr R G Lawrie for his assistance with the experimental work. The copper spheres were supplied by Dr K G Foote (Institute of Marine Research, Bergen) who also provided data for the calculation of target strengths.

Summary A series of experiments is described in which the relative target strength of brass, copper and tungsten carbide spheres is measured. The targets to be compared are suspended from the frame of a steerable 38 kHz transducer whose movement is controlled by a computer to obtain the signal from each target on the acoustic axis.

Significant differences up to 0.28 dB were found between five tungsten carbide spheres, rather more than expected from theory. Reducing the amount of nylon used to support the spheres might reduce the scatter of target strengths. No significant difference was found between two copper spheres. The mean difference between the copper and the tungsten carbide spheres was 8.69 ± 0.11 dB (95% confidence limits) which agrees with the value calculated from theory, 8.78 dB.

The absolute target strength of a brass sphere has been estimated from the relative measurements and the theoretical target strengths of the other spheres in which resonance effects are less important. The brass sphere TS for 1 ms long 38 kHz pulses is – 33.0 ± 0.2 dB, and for 0.5 ms pulses it is – 32.5 ± 0.2 dB, when the sound velocity in water is 1,491.4 m s^{-1}. The coefficient of variation with the sound velocity is + 0.02 dB s m^{-1}.

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